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Next Generation Space Telescope

Final Report
on
Robotic System Concept for On-Orbit Telescope Assembly

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Robotic System Concept for On-Orbit Telescope Assembly

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1 INTRODUCTION

1.1 Background

The Next Generation Space Telescope (NGST) is the planned successor to the successful Hubble Space Telescope (HST). It is a large aperture space telescope sensitive to near-infrared wavelengths and intended to investigate the origins of the universe. Study teams, led by NASA Goddard Space Flight Center (GSFC), TRW, Lockheed Martin and Ball Aerospace have worked on, or are in the process of working on design concepts. The baseline designs assume a single launch deployable spacecraft; however there is some interest in the potential for a robotically assembled version that could offer a larger telescope area for the same launch volume, greater deployment reliability, versatility and serviceability.

Accordingly, GSFC commissioned this NGST robotics study. It is a collaborative effort between The Boeing Company, Spar Aerospace and the University of Maryland. Spar' s effort is funded in part by GSFC under Purchase Order number S-17277-G, by the CSA under contract # 9F028-7-7641/001/XSD, and by Spar itself via internal R&D funds under work order # 96236/24001.

1.2 Purpose

The purpose of the study is to investigate the design of a NGST spacecraft design that utilizes an on-board robotic system to assemble the telescope on orbit. The goal is to analyze the operational requirements, develop a concept design for the robot system and telescope assembly, and make preliminary assessments of the critical, relevant factors of the robotic system such as performance requirements, mass, reliability etc. The study also provides inputs to a preliminary reliability comparison between robotic assembly and (mechanisms) deployment options for the telescope.

1.3 Scope

This report covers the entirety of Spar' s study effort – that funded by the CSA (SOW tasks 1.1.1 through 1.3), and the remainder of the work funded jointly by the GSFC contract and Spar' s internal R&D. It documents the following:

- investigation of the optimum approach to a robotic solution
- development of a preliminary set of design requirements
- identification of system concept options
- selection and development of the concept design
- assessment of performance

2 NGST TELESCOPE CONCEPT

2.1 Boeing Design

Boeing has created a concept design for an NGST telescope that is robotically assembled. This design as described herein, and in Reference 1, became the starting point for Spar’ s activity. Illustrations of the stowed, partially, and fully assembled configurations of this design from Reference 1 are provided in Figure 2-1, Figure 2-2, and Figure 2-3 respectively. It is recognized, however, that because Boeing’ s design has continued to evolve in parallel with this work, the NGST configuration used in this study may not capture all the changes reflected in the current Boeing NGST design.

The Boeing design concept as used in this study is as follows. The primary mirror comprises 12 petal-shaped segments that in their stowed configuration are arranged in three groups of four petals. They are stowed in upright stacks on top of the optical bench - a structural platform. In their assembled configuration, they are placed in a circular arrangement on the bench (like the petals of a flower) forming a parabolic reflector 10 meters in diameter. The secondary mirror assembly is stowed on top of the petal stacks. It comprises the mirror, its mounting, and a Stuart Platform[1] for adjusting its position and orientation when assembled. When assembled it sits near the top of a tripod, the legs of which are folded and stowed next to the petal stacks in the launch configuration. In the center of the optical bench is a telescoping cylindrical baffle. This baffle has three segments which when deployed raise it to a height of about 7.6 meters. The secondary mirror and baffle will be deployed prior to the primary mirror assembly. To achieve the stability required for the secondary mirror tripod, however, the tripod joints must be locked in some manner after deployment to ensure zero backlash.

2.2 Robotic System Architecture

The telescope design was reviewed from a robotic assembly perspective, with particular attention given to the operational feasibility. The sheer scale of the assembled telescope (10m diameter primary mirror and secondary mirror 11.5m above the optical bench) requires a special solution. In addition, concerns over contamination from the robot may require it to perform the assembly operations from the rear side of the primary mirror, i.e. below the optical bench. In order to access the various parts, and perform the construction, the robotic system concept options include:

- a large fixed base robot (with long reach and good dexterity);
- a transportable robot (i.e. with a moving base);
- a walking (inch-worm) robot; or
- a small robot, but with ingenious long reach tools

The need to lock the secondary mirror tripod struts was an important part of the operations analysis in Section 4. Typically, it means the robot must be able to reach 12m or more above the optical bench to the top joints. Possible approaches include walking up the tripod legs, or erecting a post that the robot could climb. An alternative method whereby the robot could work from the optical bench is to assemble the struts, locking them as they are erected.

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[1] A Stuart Platform is a steerable plate separated from its mounting structure by a number of linear actuators. Coordinated extension and retraction of these actuators permits adjustment of the steerable plate’ s linear and angular position. The range of motion and number of degrees of freedom in the adjustments depends on the number and arrangement of the actuators.

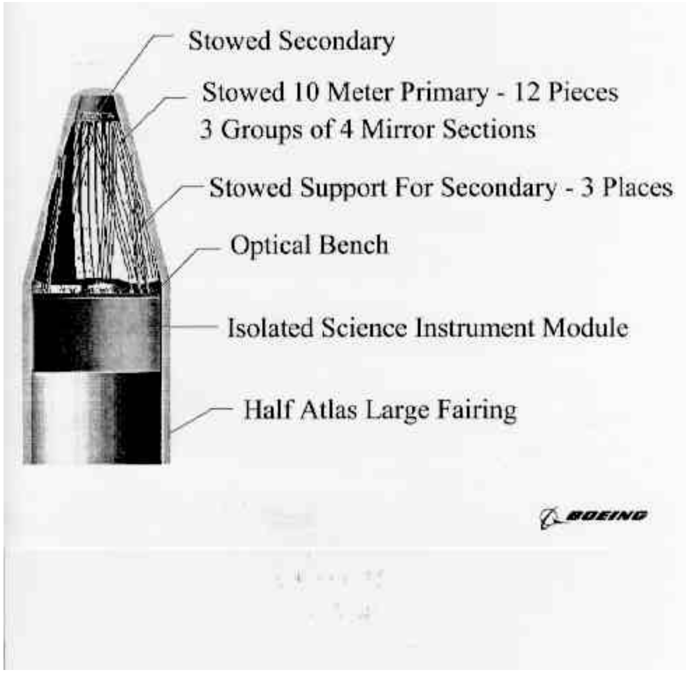

Figure 2-1 10 Meter NGST Telescope Stowed Inside Fairing

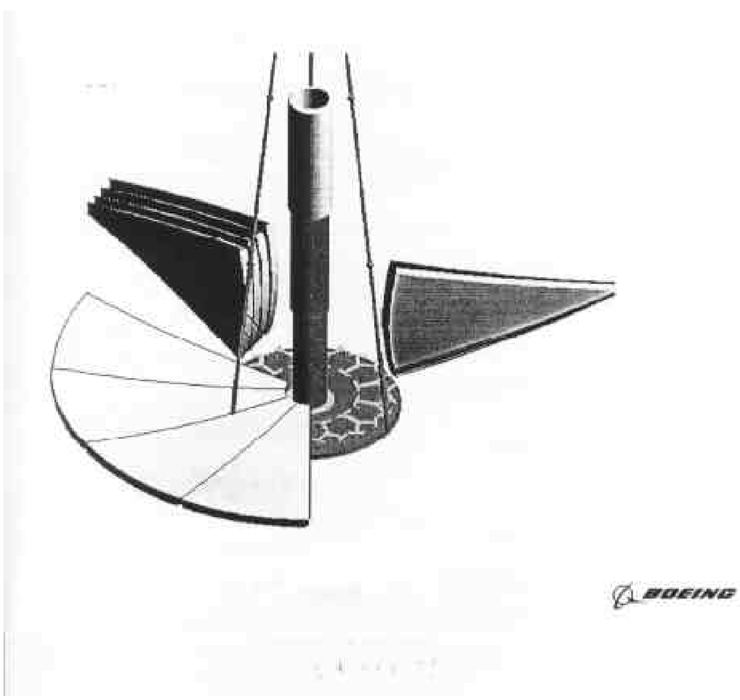

Figure 2-2 NGST Telescope Partially Assembled

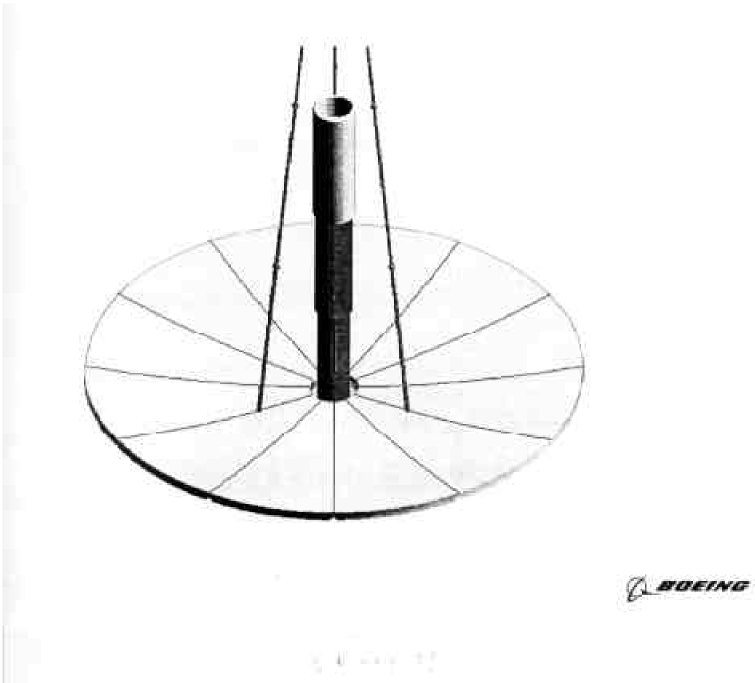

Figure 2-3 NGST Telescope Fully Assembled (Secondary Mirror Not Shown)

3 ROBOT CONCEPT

3.1 Design Goals

The major design driver for the robotic system defined by GSFC is its reliability. This is based on concerns over the reliability achievable with deploying designs, and the lack of ability to do anything about a failure in such a system when it occurs. Robotic assembly to some extent offers the capability to recover from failures. The goal for the robotic assembly approach is to demonstrate reliability that is better than that for a deployable telescope approach. The mass and cost of the robotic system at this stage of the study are secondary considerations.

In discussions with GSFC regarding these goals, it was agreed that an assembly reliability of 0.99 be considered as the minimum, with a target of 0.999. In the absence of specified mass and cost requirements for the robot system, an arbitrary target of 10% of the NGST spacecraft budget for both the mass and build cost of the robotic system was chosen. This translates to 300 kg and US$50M respectively.

For the performance of the robot system, design guidelines were drawn up to assist in achieving the mass, cost and reliability goals. Some performance numbers were assigned to such parameters as positioning accuracy, applied forces, torques etc. These were derived from the values achieved on the SSRMS and SPDM programs, modified somewhat to take into account the anticipated needs of the NGST robotic system. These design guidelines and performance goals are specified in the form of requirements in Section 5.1.

3.2 Design Issues

3.2.1 Extended Operations Set

The first issue that had to be resolved was the operational scope. Initially, extended capabilities for the robot were considered, where it could perform tasks other than simply assembling the telescope. These included deployment of the solar array, high gain antenna and propulsion boom, extension of the boom between the Isolated Science Instruments Module (ISIM) and the Space Support Module (SSM), and deployment of the sun shield. They would require a relocating (transportable or walking) robot since the physical distances between these components are too large for a fixed robot to accomplish. However, since the extended operations are not well defined at this stage, the study focussed on the telescope assembly only.

3.2.2 On-Orbit Servicing of the Telescope

The possibility of replacing failed or damaged components of the telescope during the mission was also contemplated. This too would require a relocating robot. The ISIM is at cryogenic temperatures unsuitable for storage of the robot. It also prohibits any local sources of heat so the robot could not receive any storage heating on the ISIM. The robot would therefore have to be stored in the warm portion of the spacecraft, the SSM, and traverse the boom to the ISIM in order to service the telescope during the mission. This too requires a transportation or walking capability. As with extended operations, this issue was deferred.

3.2.3 Robotic Access

As mentioned earlier, there is concern about possible contamination of the mirrors' optical surface by debris or outgassing from the robot during telescope assembly. One way to minimize this risk is for the assembly of the mirror petals to be the last operation, and to be performed with the robot on the underside of the mirror plane. Attachment of the mirror petals to the Stuart Platforms from the underside poses some specific challenges with respect to locating the petal accurately and subsequent access to the attachment fixture to tighten the interface. It also would require one of the petals to be equipped with a foothold if robotic access to the secondary mirror assembly is desired after primary mirror assembly is complete.

Working from the topside is easier from a robotic perspective, as the petals are placed from above directly on to the Stuart Platforms that can be equipped with an optical target. To avoid contamination problems, the petals could have covers that are removed as the very last operation. When assembly is complete, the robot is on the active side of the mirror. To minimize possible obscuration of the mirror, the robot can be stowed in the center of the optical bench, around the baffle. If it cannot be stowed on the topside, then it must walk around the petals to the rear side.

At the time of performing the operations analysis, Boeing' s baseline was to assemble the primary mirror from the underside of the bench.

3.2.4 Walking Robot or Not?

To investigate this issue, distinction was made between three categories of robot system: a fixed base robot, a transported robot, or a walking robot. The definitions for each type are as follows:

- **Fixed Base Robot** - a robot that operates from a single fixed location. It is attached to that location in its launch configuration, then deploys and performs all the assembly activities from that location.
- **Transported Robot** - a robot that is permanently attached to some structure, limbs or mechanisms that physically move its base so that it can access other locations. This relocation is independent of the robot motions.
- **Walking Robot** - a robot that can self-relocate. It travels from location to location by stepping end-over-end from one foothold to another. It requires an end effector at each end, and a number of footholds placed appropriately that have power and data connections.

a) Fixed Base Robot

There is no specific need for mobility for the robot if extended capabilities are not part of the requirements. However, the size of the telescope means the fixed robot will require a very long reach capability combined with high dexterity in order to access all the components and perform the assembly operations. The secondary mirror structure, for example, rises 11.5m above the optical bench. This suggests a very large and possibly complex robot. The operational design may be difficult to enable it to reach around the partially constructed telescope as it nears the completion of the assembly. Stowage volume and length restrictions may conflict with the need for such a long reach robot.

b) Transported Robot

This concept employs a (potentially) small dexterous robot that is moved to where it needs to be, and is supported while it does its work. This concept is not unlike the Special Purpose Dextrous Manipulator or SPDM on the end of the Space Station Remote Manipulator System, (SSRMS).

One "transported robot" concept utilizes a rotating base. This could be achieved by means of an annular ring on the underside of the optical platform. The capability to move the base to any circumferential position would allow access to all sides of the telescope, thus reducing the reach and dexterity requirements for a non-walking robot system.

Another "transported robot" concept is one that employs an articulated base. This base is essentially the addition of another couple of degrees of freedom, allowing the shoulder joints to be positioned on different sides of the optical bench facilitating access to all sides of the telescope. An extending base option was envisaged with an axial extension of the base, raising the robot high above the optical bench, but it is doubtful that this could provide the access required to all sides of the telescope. Some means of bringing the whole system from the rear side of the bench is also necessary, and the means of achieving this efficiently and effectively is not obvious.

As with all non-walking solutions, the transported robot is restricted to the construction of the telescope. It cannot access other parts of the spacecraft to perform extended capability tasks. It also cannot be kept warm after assembly (with keep-alive power), as it is located near the telescope and would be a heat source degrading the instrument' s performance. Therefore, it cannot be used to service the telescope after assembly.

c) Walking Robot

A walking robot has both advantages and disadvantages. It can move its field of operation as required, and is operationally much more versatile. On the down side, it is typically more complex than a fixed (non-walking) robot, and is somewhat larger and less dexterous because the wrist and shoulder must be identical for walking. They must be sized according to the higher loads that will be experienced when that end is acting as a shoulder and supporting the arm plus payload at its root. A fixed robot can have a tapered size, i.e. the elbow smaller than the shoulder, and the wrist joints smaller than the elbow. The loads at the wrist are smaller than at the shoulder. The end effector too can be smaller. The result of a smaller wrist and end effector is greater dexterity and an ability to access workspaces that are more restricted.

The walking robot also requires a full complement of wiring end to end thus increasing cable harness size. This can be a significant contribution to the overall mass of the system, though the use of fibre-optic cables for the data harness can mitigate it to some extent. Footholds must be provided wherever the arm is to step, providing power and data connections as well as mechanical support. These require strong attachment locations, and connections to a power and data bus that must be run wherever the footholds are located. There is an associated mass and cost overhead.

Operational versatility greatly favors the walking robot. While mass and cost concerns would tend to favor a fixed or transported system solution, these are not design-driving criteria at this stage of the study. The walking robot must repeatedly engage and disengage end effector connectors. Resulting reduction in reliability may be counterbalanced by its operational versatility, which gives it workaround capabilities.

One major challenge is the need to reach over 11m above the optical bench to access the secondary mirror. Not only does the mirror have to be raised to that height, but the joints of the legs of its supporting tripod also must be locked to achieve the necessary rigidity (zero backlash) after deployment. If the robot is to reach the secondary mirror from the bench, it must have a very long reach (>=12m), or must be able to climb up a structure. Now the fairing diameter of 3.5m effectively limits robot boom length to about 3m, so it would require a robot with four booms (two extra elbow joints to reach that high from the bench. This significantly increases cost and complexity, makes control of the robot more challenging, and stowage more difficult. The extra joints have little purpose other than to allow the booms to fold for storage. Some consideration was given to the potential for driving the secondary mirror deployment from the bench by a fixed robot utilizing an extension tool or device such as a rack and pinion. These are not very practical due to their size, and the desire for slim tripod legs to minimize blockage of the primary mirror.

Based on the specified requirements, and the baseline telescope design, a walking/climbing robot is the recommended solution.

3.2.5 Reaching the Secondary Mirror

The robot design baseline has a kinematic configuration based on the SPDM and with two 3-meter booms (limited by the maximum stowage length). The effective reach of the robot is 6 meters from wrist pitch joint to wrist pitch joint. Therefore, at least one step-up is required to reach 11.5 meters. Three approaches were considered for access to the secondary mirror: climbing up the legs of the secondary mirror tripod; piecewise assembly of the tripod; and use of a climbing post.

a) Climbing the Tripod

This solution involves incorporating footholds into the legs of the secondary mirror tripod. It allows direct and simple access to the mirror. There are some potentially challenging issues to consider. The size of the footholds could cause blockage of the light path, and may complicate stowage of the tripod. The electrical (power & data) harness supplying the foothold will have to cross at least one hinge on the tripod. At the extreme cold temperatures expected, the bending stiffness of this wiring could significantly inhibit the tripod deployment.

Finally, to support the loads imposed by a robot walking on it and working from it, the tripod may have to be strengthened. This could add size and mass to a structure that also has a primary requirement to be as small and thin as possible.

b) Piecewise Assembly

A completely different approach is the piecewise assembly of the secondary mirror structure. Here the tripod is put together in sections from the bench (the top pieces first), temporarily standing it on the bench, and gradually raising it as each new set of leg sections is attached. The leg joints are locked as it is assembled. This is operationally more complex, requiring more assembly steps, but is certainly feasible. It has been estimated that the required robot length would be 8.0 meters, which (as a 2-boom robot) cannot be stowed inside the fairing. The robot could be a 3-boom design, though this would mean more joints, more mass, more complexity of control.

c) Climbing Post

An approach that does not adversely affect the secondary mirror tripod design, and is operationally simple is to combine a 6-meter walking robot with a climbing post. This post would be in addition to the robot and the telescope, and it would be erected by the robot prior to assembly of the secondary mirror structure, and removed afterwards. It would have to be assembled in two pieces since the stowed limit on its length would also be approximately 3 meters. The post would plug into a foothold on the optical bench and would have a foothold at its top, close to the full reach of the robot. On the down side, addition of hardware (the post) not contributing to the telescope, adds weight to the overall mission, and adds electrical connections that will detract a little from the overall system reliability.

A variation on the above option utilizes a telescoping post such as a STEM device. The STEM would be stowed on or under the optical bench, and be extended by the robot or by its own drive system. This has more mechanisms than the erected post concept, but fewer electrical connections. A trade would be required to assess the cost, mass, size, reliability etc. of each, and determine if this is a preferred solution.

At the time of performing this trade, a viable method of assembling the secondary mirror by climbing the tripod had not been developed, though Boeing were proposing to investigate it further. The trade performed was between options (b) and (c). To help make this final selection between the piecewise secondary mirror assembly and that of employing a climbing/telescoping post, operations sequences were generated for both. These can be found in Section 4. When comparing the two options for secondary mirror deployment, method 1 (piecewise assembly) requires:

- a robot of length (wrist pitch to wrist pitch) of 8m (to reach and adjust strut hinges at the secondary mirror platform)
- the top struts to be adjusted and locked after secondary mirror assembly is removed from bench, as the angles with the mirror platform will be incorrect at that point
- 7 relocations (step-overs) of robot
- 15 grapples (locking of two struts is performed during primary mirror assembly)
- 8 operations of moving and positioning of objects

Method 2 (utilizing a climbing post) requires:

- a robot of length (wrist pitch to wrist pitch) of 6 meters
- a 6 meter high post (two 3 meter pieces, or hinged in the middle)
- 3 relocations (step-overs) of robot
- 17 grapples (locking of two struts is performed during primary mirror assembly)

- 5 operations of moving and positioning of objects

From this it can be seen that the second method is simpler, with fewer operations, and can be accomplished with a 6-meter robot. The first method is more complex and requires an 8-meter robot that cannot readily be stowed as a two-boom design. The "climbing post" option has therefore been chosen as the baseline.

3.2.6 One Robot vs. Two

Significant consideration was given to whether one or two robots would offer a better solution. The main basis behind a two-robot solution is the perceived increase in reliability by having a back-up robot. If the second robot can always remove the first when it fails and subsequently complete the mission, and, if each robot is one fault tolerant, then the system itself becomes three-fault tolerant. On the down side, there will be a mass and cost penalty for adding another robot. Since mass and cost are secondary considerations at this stage of the project, the focus has been on reliability. The reliability analysis is described in Section 6.1.

It may be the case that in some instances the second robot will be unable remove the first robot and complete the mission, though significant design must be expended to minimize the chance of any such occurrences. The most likely instance of this may be where the first robot fails while it is moving a component in free motion. Release of the end effector would cause the component to float free, an unacceptable result. The component must therefore be first secured in some way. The component must have a secondary grapple fixture whereby the backup robot can grapple it, such that it can position and insert the component into its destination location (or some temporary restraint). This has to be accomplished while the first robot is still attached, overcoming any resistance it might provide, including joint brakes (if these cannot be released). Additional camera views may be necessary for this non-nominal operation. This scenario would also drive the number of footholds needed since extra footholds may be required to allow the second robot access to the failed robot and component wherever the failure might occur, and wherever the component must be placed. Attachment locations are required for both the component, and for the failed robot that must be removed, and stowed out of the way. Note that the second robot cannot walk while carrying the component or the failed robot, so storage locations must be close by. Accomplishment of this type of recovery will be operationally challenging.

The reliability calculations versus the requirements of 0.99 minimum and goal of 0.999 will strongly determine which approach is favored.

3.2.7 SPDM / SSRMS Design Heritage vs. New (Application-Specific) Design

To minimize costs it has been proposed that Spar robotic design heritage be utilized by making only minimal changes to an SPDM or SRMS design. Boom lengths would have to be changed to achieve the required reach and meet the stowed length limitations. To save mass, joint sizes could be scaled down. The end effectors would be replaced with a smaller, simpler and less expensive option, designs for which are currently under development. Some changes may be imposed by the design of the NGST spacecraft.

Even the seemingly smallest of changes to the existing arm design (e.g. scaling down sizes of joints) can add significant non-recurring costs. The resulting system is usually still a compromise between the original design, and the optimum design. It can be more cost effective, and offer better performance to design an application-specific (custom) robot system. A trade is necessary to determine the optimum approach. This needs to be performed in subsequent study work.

4 OPERATIONS SEQUENCES

The telescope assembly may take place in transfer orbit, or after the spacecraft has achieved its final orbit at the L2 libration point. Where it is performed does not affect the telescope assembly sequence. However, there must be no significant accelerations from orbit corrections or stationkeeping burns while the assembly operations are in progress. No determination has been made at this point whether the assembly should be performed in sunlight or in the shade. The chosen condition will be achieved via the state of the sunshield (deployed or stowed) and the orientation of the spacecraft. The robot will require sufficient heating to protect its electronic and mechanical components from cold temperature extremes. Worksite illumination must be provided for assemblies in either shade or sunlight, to ensure appropriate lighting conditions for the video cameras.

The following sections describe operations scenarios for the telescope assembly.

4.1 Standard Starting Sequence

1. Spacecraft systems check out for assembly readiness (power, communications available)
2. Warm up of robotic system to operating temperatures
3. Robot system initialization and static check out
4. Opening of container / removal of shroud/blanket/cover
5. Release of robot launch restraints, release of robot end effector (hand)
6. Check out of robot motion and vision systems

4.2 Secondary Mirror Assembly

Two approaches to the secondary mirror assembly are considered - use of a climbing post, and piecewise construction. These were selected in the earlier trade-offs (Section 3.2.5).

4.2.1 Method #1 - Piecewise Construction

This method attempts to build the secondary mirror tripod by successively adding sections to the feet of the tripod, gradually extending the secondary mirror assembly upwards. It is assumed the tripod is attached to the optical bench at appropriate locations and specific orientations to permit this, and that the tripod leg sections are stowed on top of the optical bench.

9. Step over to foothold BP1 on optical bench
10. Pick up first middle strut (M1) and insert into holder at edge of optical bench (angled out)
11. Step over to foothold BP2
12. Grapple and unlatch base of top strut T2
13. Step over to foothold BP3
14. Grapple and unlatch base of top strut T3
15. Step over to foothold BP1
16. Grapple and unlatch base of top strut T1, and pick up tripod and mirror assembly
17. Move assembly to top of strut M1 and attach

18. Reach up to attachment of strut T1 to mirror assembly, adjust angle of hinge and tighten
19. Reach up to attachment of strut T2 to mirror assembly, adjust angle of hinge and tighten
20. Reach up to attachment of strut T3 to mirror assembly, adjust angle of hinge and tighten
21. Step over to foothold BP2
22. Pick up second middle strut M2
23. Move it to base of strut T2 and attach and tighten
24. Step over to foothold BP3
25. Pick up third middle strut M3
26. Move it to base of strut T3 and attach and tighten
27. Pick up first lower strut L1
28. Move it to holder in bench, insert and lock (at final angle)
29. Reach to base of M1, grapple assembly, unlock and remove from bench
30. Move assembly to top of strut L1 and attach and lock
31. Pick up strut L3 and attach to base of M3 and lock
32. Grapple other end of L3 and attach to optical bench and lock
33. Step over to foothold BP2
34. Pick up strut L2 and attach to base of M2 and lock
35. Grapple other end of L3 and attach to optical bench and lock

4.2.2 Method #2 - Climbing Post

This assembly method utilizes a climbing post for access to the secondary mirror. The post is stowed on the spacecraft in two sections (each approximately 3 meters in length). It is installed on the optical bench by the robot that then uses it as a platform to reach to the height necessary for secondary mirror assembly. With a few minor changes, this scenario can also apply to the use of a telescoping post. The stages are illustrated by means of Figure 4-1 and Figure 4-2, which have been taken from Reference 1, and modified to include a representation of the robot.

9. Step over to foothold BP1 on optical bench
10. Pick up post base section
11. Install post base on top of optical bench
12. Pick up top section of post (see Figure 4-1)
13. Install top section on top of base section
14. Step onto foothold on top of post (BP4)
15. Reach down and grapple secondary mirror assembly
16. Raise secondary mirror into position 11.5m above bench (struts lock over-center)
17. Grapple each (of 3) strut hinges on secondary mirror platform in turn, and tighten to lock

18. Grapple each (of 3) hinges between upper two levels of tripod struts in turn, and tighten to lock (see Figure 4-2)
19. Step down to BP1
20. Grapple and remove top section of post
21. Stow top section of post
22. Grapple and remove base section of post
23. Stow base section of post
24. Grapple and lock lower two hinges of struts of nearest tripod leg

4.3 Completion of Assembly (Primary Mirror, Baffle)

The next phase of the assembly is that for the primary mirror and baffle. Most of this is common to all of the options, except that for efficiency, some locking of the tripod joints can be done during primary mirror assembly to save unnecessary relocations of the robot. The stages are illustrated by means of Figure 4-3 through Figure 4-7, which are also modified drawings from Reference 1.

101. Grapple top of petal stack #1 and release launch restraints
102. Grapple bottom of petal stack #1 and release launch restraints
103. Rotate petal stack #1 out to side of bench, and release
104. Step over to foothold BP2
105. Grapple and lock lower two hinges of struts of nearest tripod leg (for post option only)
106. Grapple top of petal stack #2 and release launch restraints
107. Grapple bottom of petal stack #2 and release launch restraints
108. Rotate petal stack #2 out to side of bench, and release
109. Step over to foothold BP3
110. Grapple and lock lower two hinges of struts of nearest tripod leg (for post option only)
111. Grapple top of petal stack #3 and release launch restraints
112. Grapple bottom of petal stack #3 and release launch restraints
113. Rotate petal stack #3 out to side of bench, and release (see Figure 4-3)
114. Grapple central baffle and release launch restraints
115. Raise baffle to full height and lock in position (see Figure 4-4)
116. Grapple rear petal on stack #3 and release restraints
117. Move petal to Stuart Platform #3-4 and insert it into V-guides such that petal is positively engaged but not tight (see Figure 4-5)
118. Release petal, grapple Stuart Platform bolt, tighten up petal mounting and release
119. Repeat last three steps for remaining three petals in stack #3
120. Step over to foothold BP2

121. Grapple rear petal on stack #2 and release restraints
122. Move petal to Stuart Platform #2-4 and insert it into V-guides (petal is positively engaged but not tight)
123. Release petal, grapple Stuart Platform bolt, tighten up petal mounting and release
124. Repeat last three steps for remaining three petals in stack #2
125. Step over to foothold BP1
126. Grapple rear petal on stack #1 and release restraints (see Figure 4-6)
127. Move petal to Stuart Platform #1-4 and insert it into V-guides such that petal is positively engaged but not tight
128. Release petal, grapple Stuart Platform bolt, tighten up petal mounting and release
129. Repeat last three steps for remaining three petals in stack #1, completing telescope assembly (see Figure 4-7)
130. Step over to storage foothold
131. Robot re-stows itself and is switched off

Figure 4-1 Robot Preparing to Install Top of Post

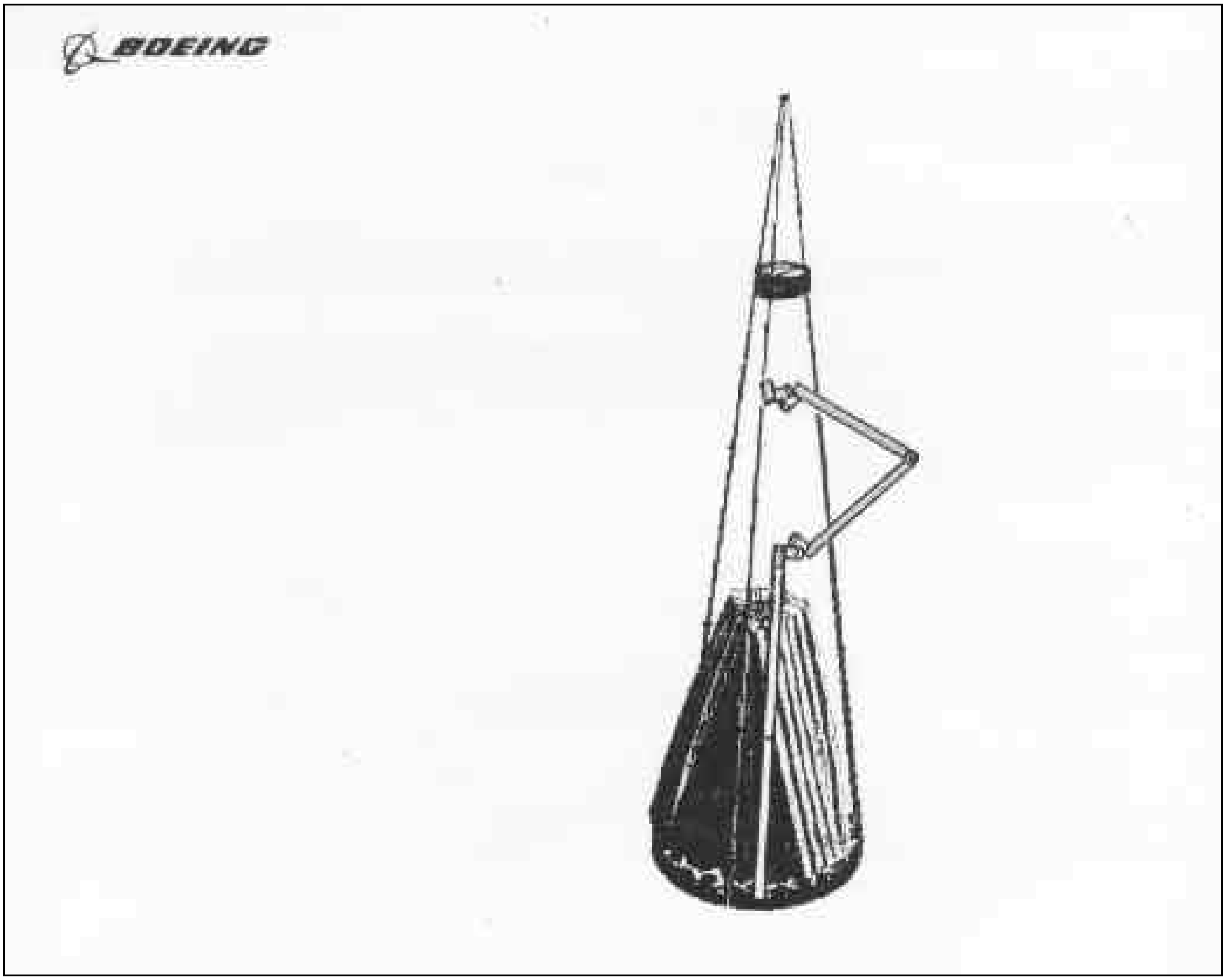

Figure 4-2 Robot on Top of Post, Tightening Tripod Leg Joints

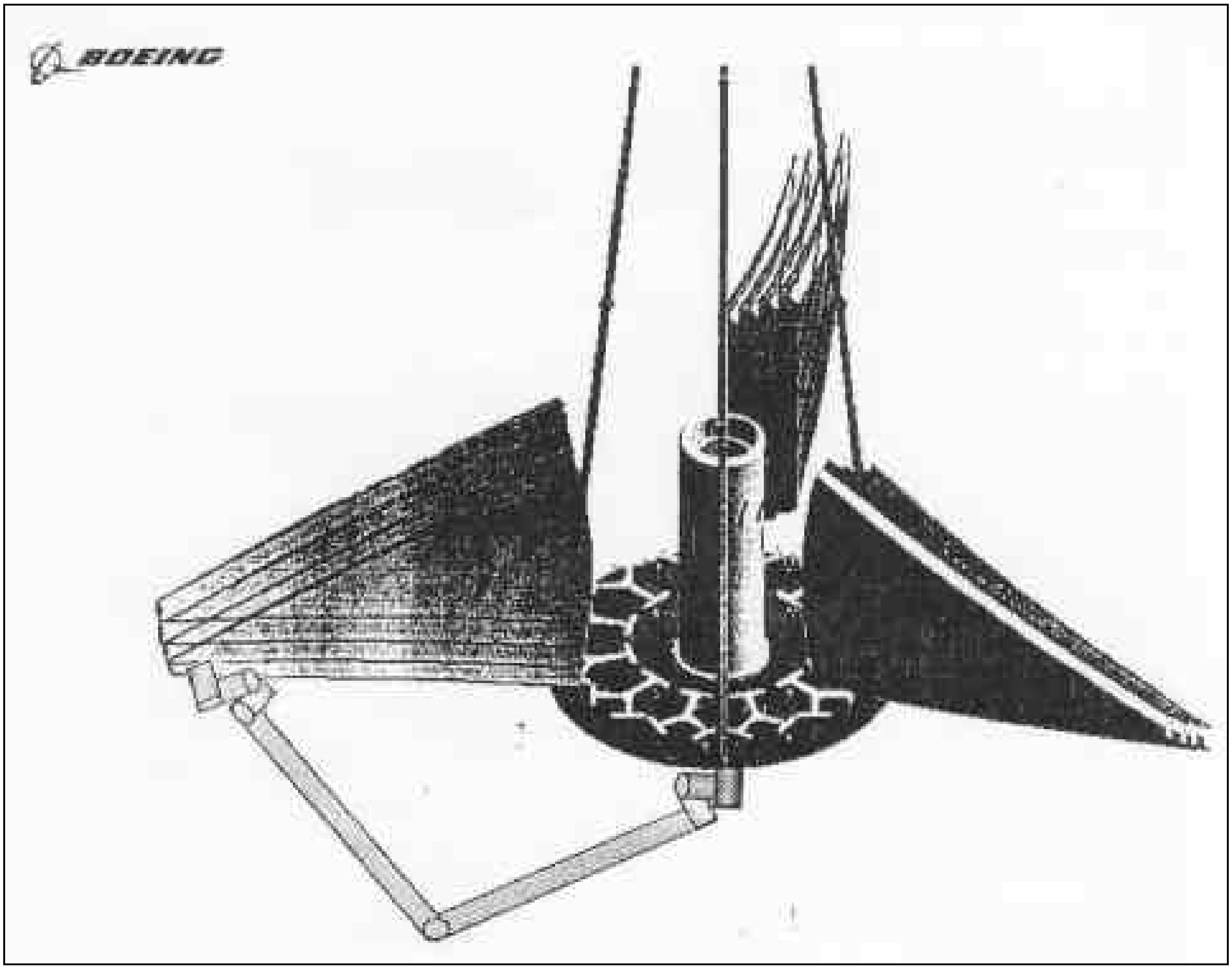

Figure 4-3 Robot Rotating Third Stack of Petals

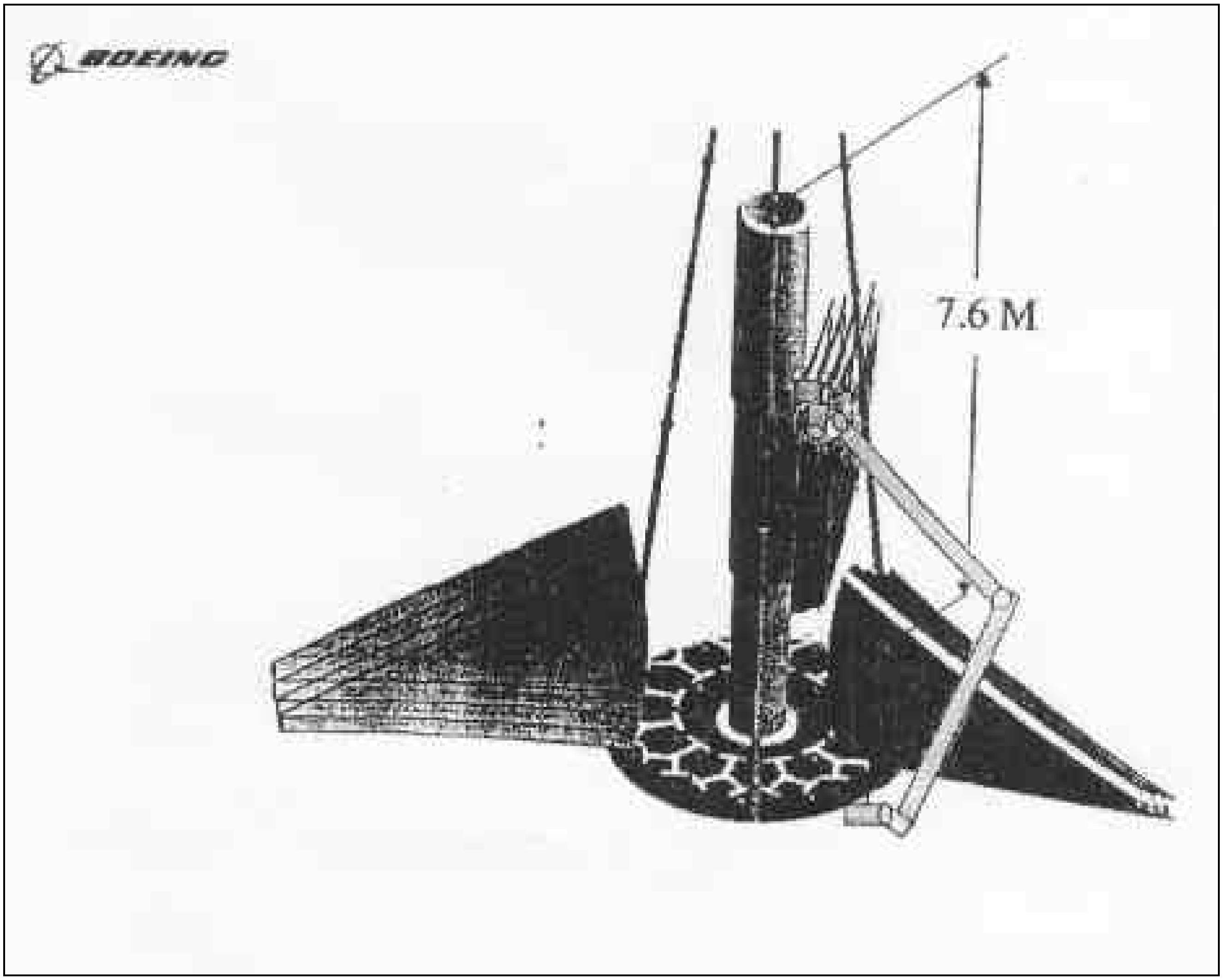

Figure 4-4 Robot Raising Central Baffle

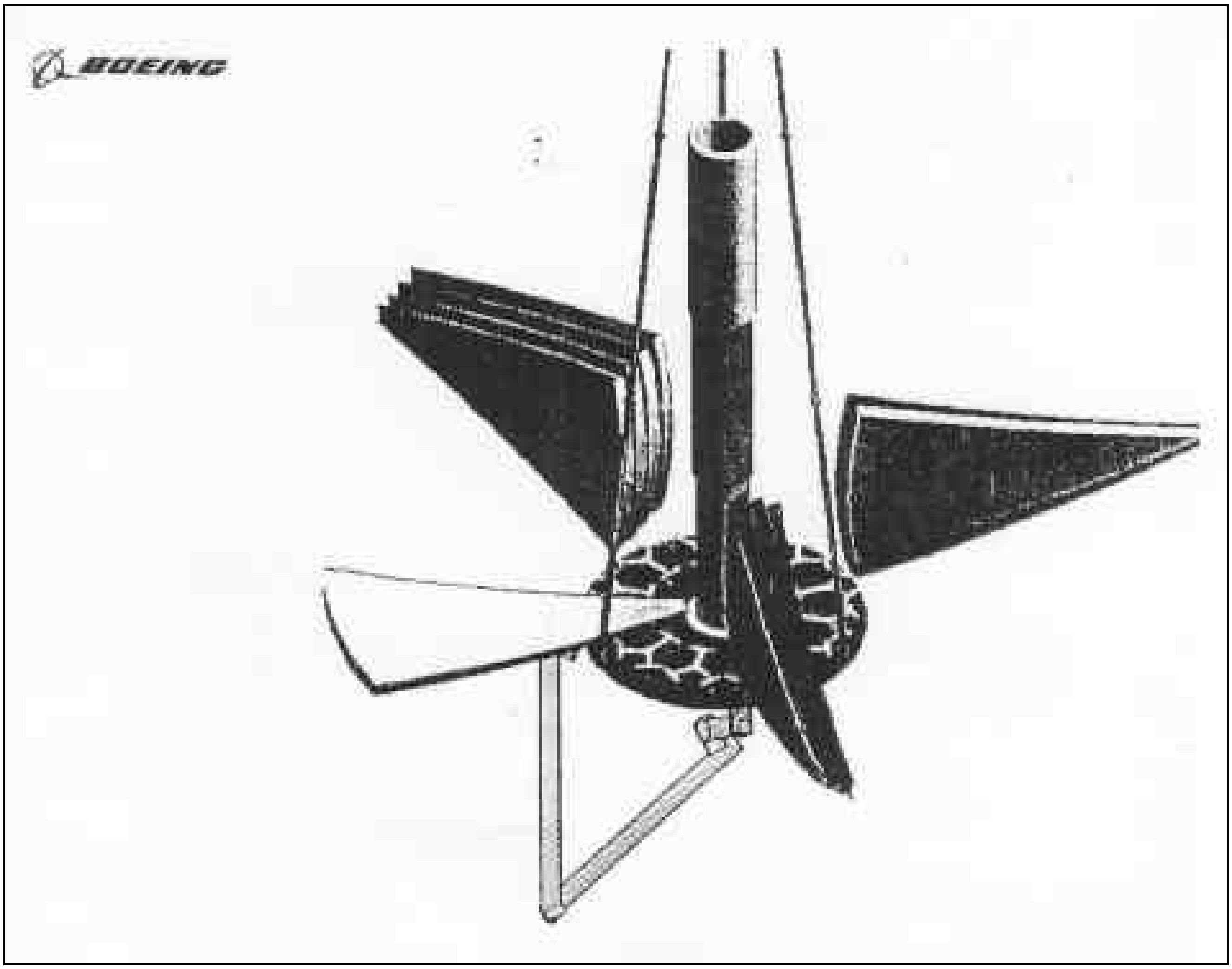

Figure 4-5 Robot Installing First Petal on to Stuart Platform

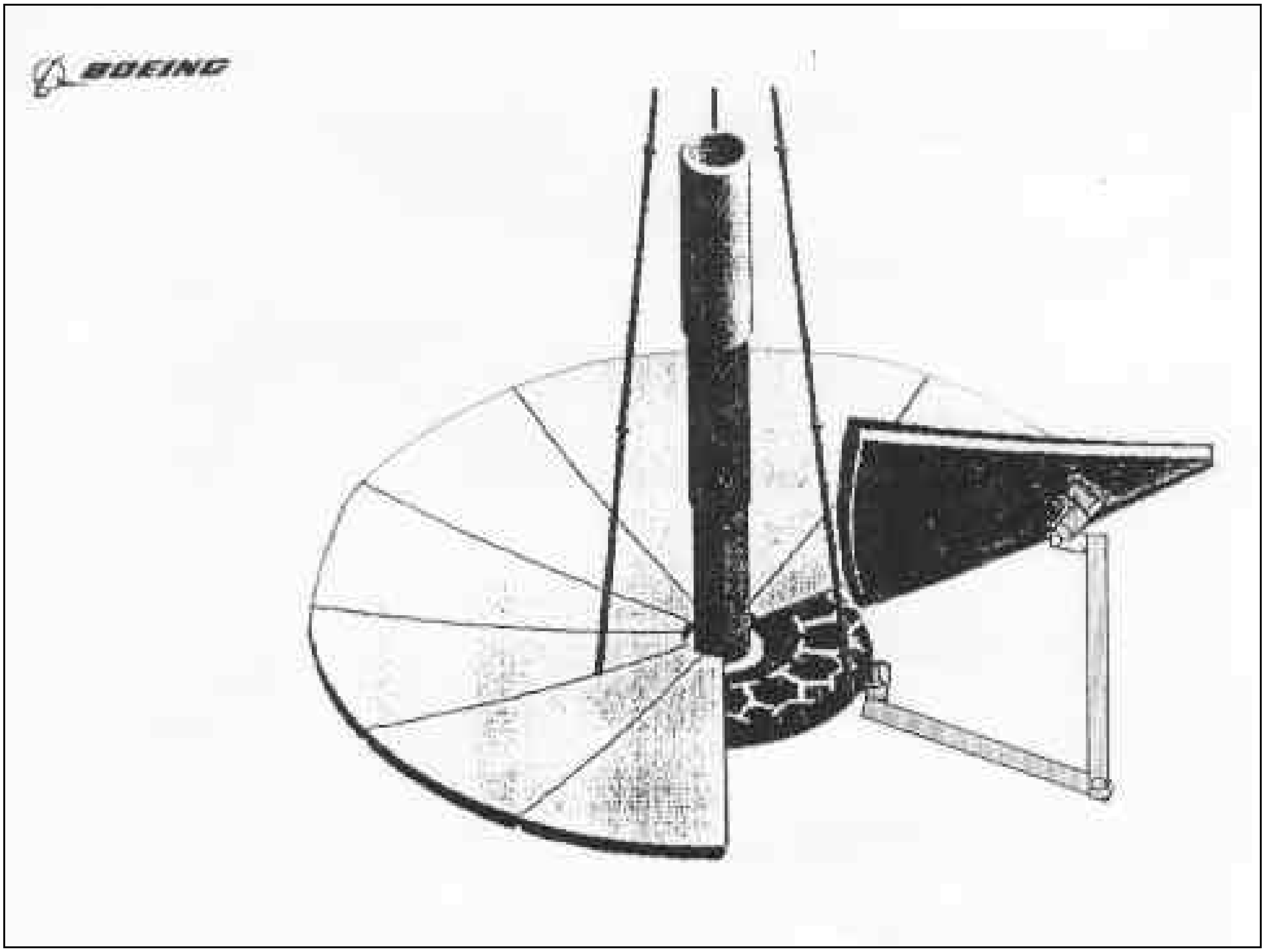

Figure 4-6 Robot Installing First Petal of Final Stack

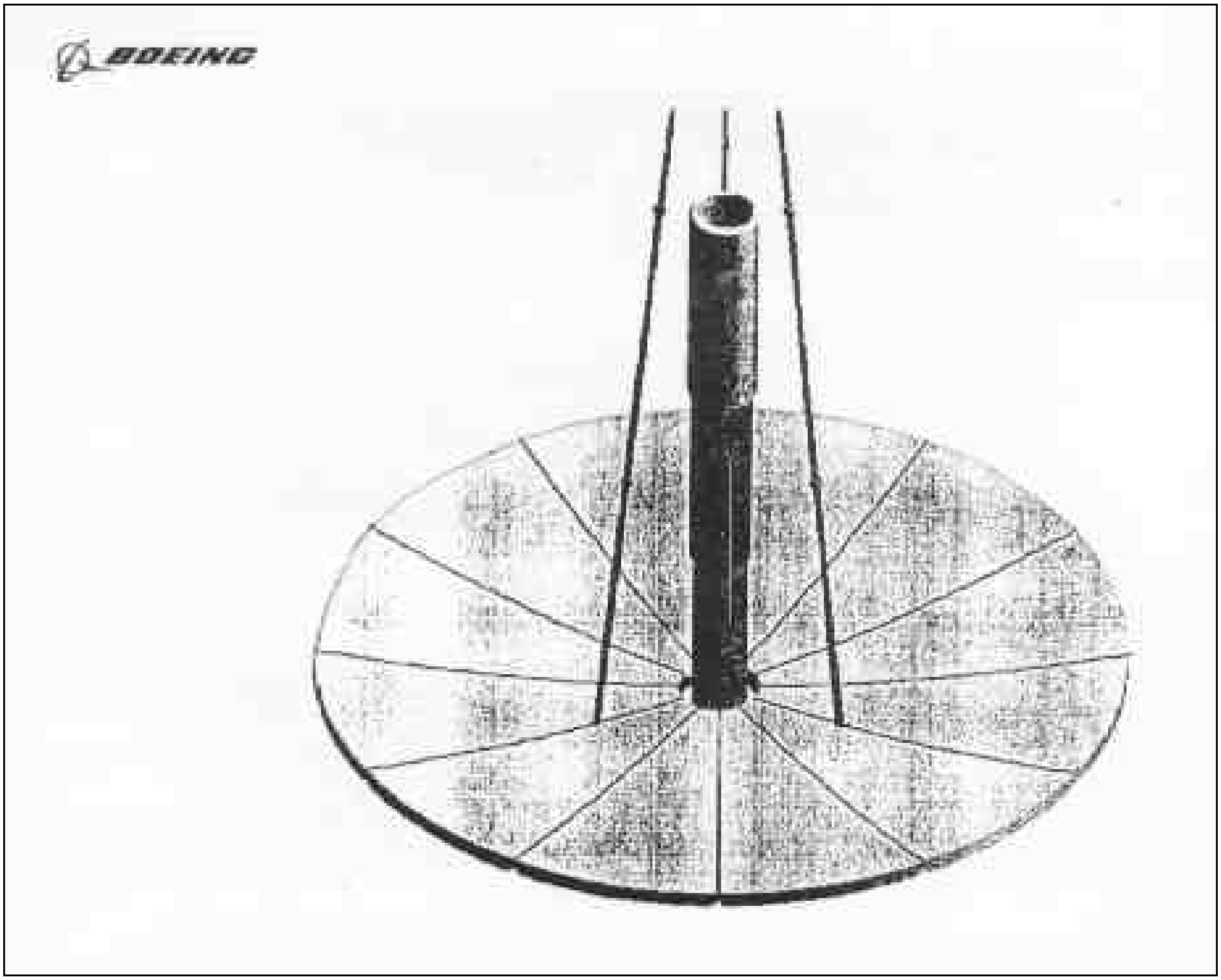

Figure 4-7 Telescope Assembly Complete (Secondary Mirror not Shown)

5 ROBOTIC SYSTEM DESIGN

The development of the robot system design needs to be performed iteratively and in close conjunction with the telescope design. The system comprises the robot, the interface hardware and the ground operator workstation. As a starting point for the robot, the joint configurations will be based on the SPDM for dexterity. Boom lengths must be greater to achieve the reach. Boom and joint diameters can be reduced from SPDM-like dimensions since the load requirements will be smaller. An end effector must be located at each end of the arm to enable walking. This end effector design is based on a concept under development by Spar that is robust yet in a small package compatible with the Spar micro fixture and suitable for dexterous assembly operations. The footholds and handholds will be based around the Spar micro fixture – a space-qualified component as described in Section 5.3.2. The ground operator workstation design is beyond the scope of this contract, though some general observations have been addressed in Section 6.8.

The requirements and design goals for the NGST robotic system are immature at this stage. An attempt to define and quantify the requirements has been made below. These numbers must be treated as a preliminary benchmark, and are contingent on the telescope design and assembly method, both of which are not baselined at the time of writing.

5.1 Requirements

With an understanding of the telescope design and assembly operations, a set of robotic system design requirements was generated. These are:

a) Robotic system reliability of 0.99 for the assembly mission
b) Minimize the number of step-overs required by the robot to perform assembly.
c) Minimize the number of footholds required by the robot to perform assembly.
d) Avoid placement of footholds on movable/detachable structures
e) Minimize the number of grapple and release operations required for assembly
f) Minimize footprint of footholds/handholds for compactness
g) Select camera locations and functions to minimize number of cameras required
h) Minimize number of sensors (e.g. force moment sensors, microswitches etc.) required to complete mission (not referring to redundant sensors).
i) Minimize number of actuators - includes robot joints, end effector (gripper, nut runner, advance system), active tools, pan & tilt units etc.
j) Use minimum force and moments to perform assembly operations (use self-reacting EE/tools if possible)
k) Bolting force applied by end effector nut runner and reacted through jaws and grapple fixture
l) Design assembly to avoid need to work in awkward configurations / restricted work spaces
m) Minimize the number of operations & number of steps in each assembly operation
n) Minimize operational performance requirements (relaxed performance)

5.2 Design Goals

Based on the requirements above, a set of design goals was created. This is an attempt to put numbers against the requirements in order to develop a quantitative understanding of the system design. The lettering corresponds with that of the requirements section.

a) Robotic system reliability goal of 0.999 for the assembly mission

b) A maximum of 8 robot relocations (step-overs)

c) A maximum of 5 footholds (placed as far apart as possible) to complete mission. Includes stowage foothold, but not redundant footholds added for reliability reasons.

d) Zero footholds on movable structures

e) A maximum of 40 grapple and 40 release operations for the robot for total system assembly (does not include step-overs)

f) Locate electrical connectors and targets directly adjacent to grapple fixtures

g) A maximum of eight cameras to complete mission (not including redundant cameras).

h) Suggested maximum number of sensors TBD (1 per non-robotic mechanism).

i) Minimum number of actuators TBD

j) A maximum of 10 N force and 5 Nm moment to be applied by the robot in free motion

k) A maximum of 50 Nm torque capability for the end effector nut runner

l) Minimum workspace envelope for end effector to access components - 0.5m diameter, 0.5m deep

m) TBD maximum number of operations & number of steps in each operation

n) Operational performance limits:

Positioning accuracy	TBD (25mm)
Positioning repeatability	TBD (13mm)
Applied Force (Static)	TBD (25 N)
Applied Torque (Nut runner) (Static)	TBD (50 Nm)

n) Two configurations of launch volume have been suggested by GSFC. The first is a rectangular box 1m x 1m x 3m, which may be split in two for a 2-robot system (Figure 5-1). The second comprises two nested boxes of half the size, split in two, with each half of each box angled to the other by 30 to 60 degrees in a V-shape (Figure 5-2).

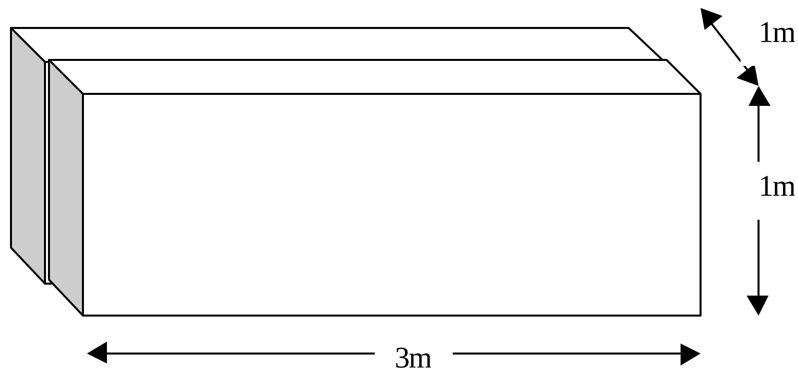

Figure 5-1 Rectangular Robot Stowage Envelope

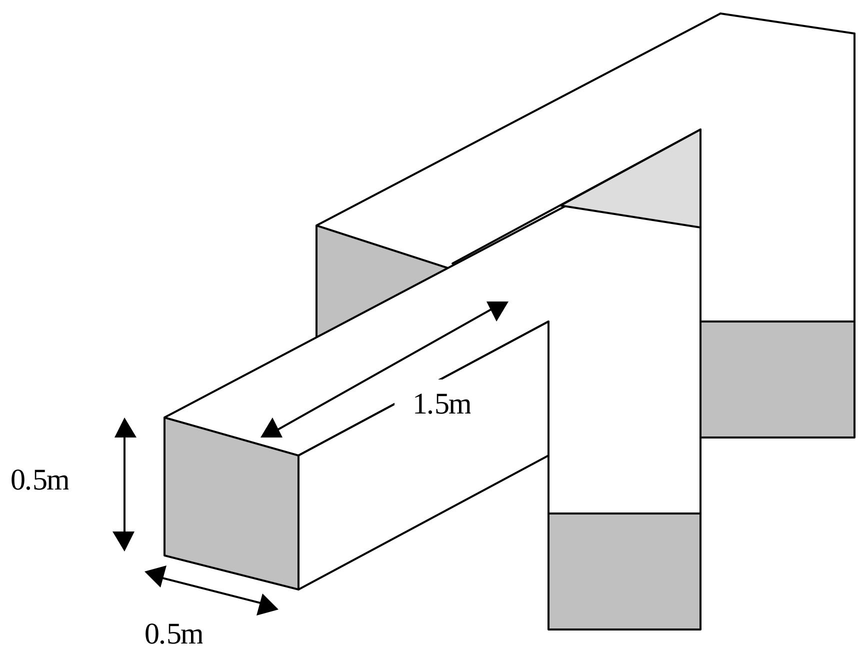

Figure 5-2 Nested V-Shaped Robot Stowage Envelopes

5.3 System Configuration

Based on the design goals in the previous section, discussions with the Boeing design team responsible for the telescope design, and operations analysis, the system configuration has been defined as follows.

- the robot needs both long reach capability (>6m) and dextrous operations capability
- the robot must have the ability to walk
- the robot may need a set of special tools to perform the assembly tasks
- the robot must be scaled down in size from SSRMS or SPDM-like dimensions (referring to boom, joint diameter and mass) to fit the available envelope
- the use of an assembled or telescoping post to provide access to the secondary mirror
- cameras in different locations perform multiple tasks and provide back-up, rather than redundant cameras at each location, or cameras performing only one task. Cameras on robot perhaps with pan and tilt units to provide for versatility in views to operator. Short focal length cameras on end effector for grapple operations and for inspection. Additional fixed worksite cameras for view of entire work area
- provision must be made to allow the second robot to remove the first robot if it fails, and still complete the mission, regardless of the configuration or location in which the failure occurs

5.3.1 Robot Design

The robot design concept has been based on a single arm of the SPDM. The rationale here is that it is desirable to utilize the MSS design heritage to minimize development costs. The SPDM was chosen over the SSRMS since it has been specifically designed for dexterous operations similar in nature to those required in the assembly of the NGST telescope. The major configuration changes are a reduction in size and strength, and an increase in length (reach). These will be accomplished by smaller (scaled down) joints and extended booms. A preliminary estimate suggests boom, joint and end effector diameters of 0.15 m. The length of the manipulator from elbow pitch to each wrist pitch is 3.0 m, and each end effector length approximately 0.35 m. This gives a robot total length of approximately 7.0 m. The joint kinematics are assumed unchanged. The NGST robot will have end effectors at both ends. These will be more compact than the SPDM end effectors, and designed specifically to interface with the Spar micro fixture. The micro fixture is proposed as the basis of the footholds and handholds, and for any bolt or latch interface that the robot must operate. An illustration of the robot concept is provided in Figure 5-3. A more accurate representation of the joint geometry is shown in Figure 5-4 and Figure 5-5 – pictures of the 3D model of the robot in its deployed and stowed configurations respectively.

The 3D model of the concept has been created using the Pro Engineer software package. A similar model of the telescope has been proposed, with the intention of combining the two models and performing a kinematic analysis of the assembly operations. Such an analysis would validate the approach, generate much more detailed operations sequences, and determine requirements for the robot such as reach and dexterity. The combined models could also be used to generate a video of the assembly sequence. An illustration of the NGST robot performing the telescope assembly is shown in Figure 5-6.

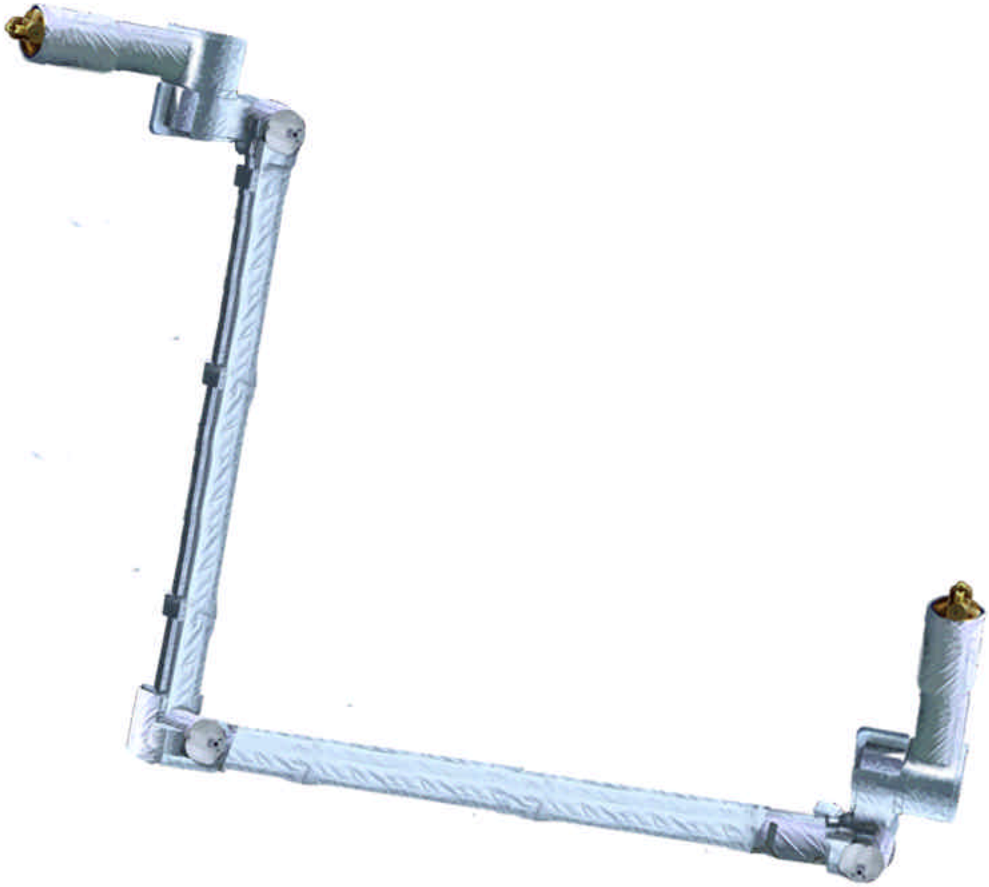

Figure 5-3 NGST Robot Concept Illustration

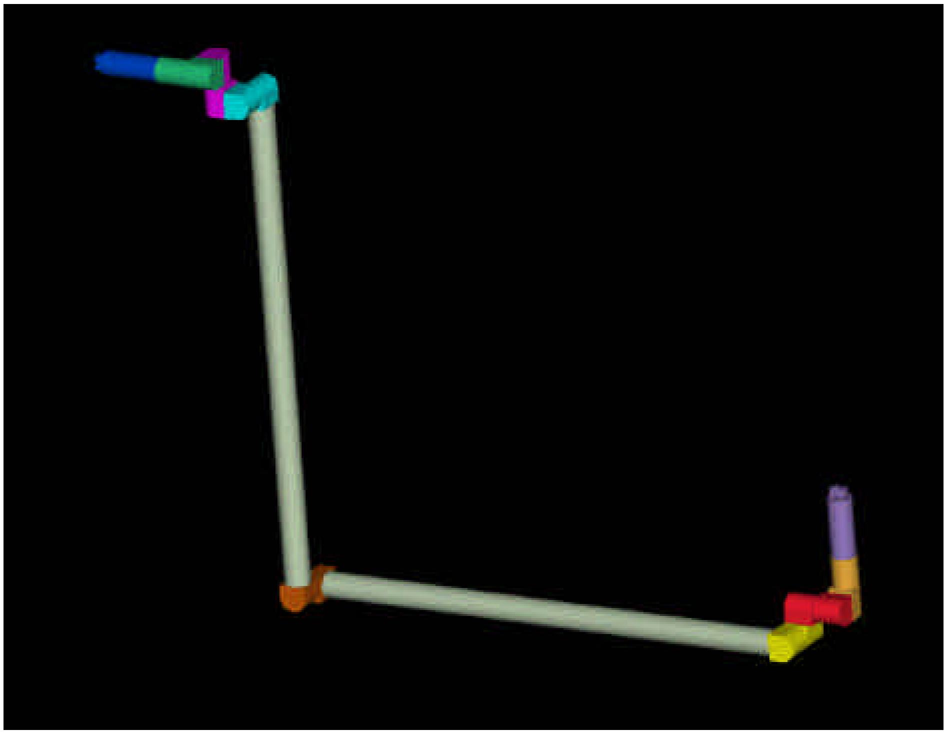

Figure 5-4 Robot 3D Model (deployed)

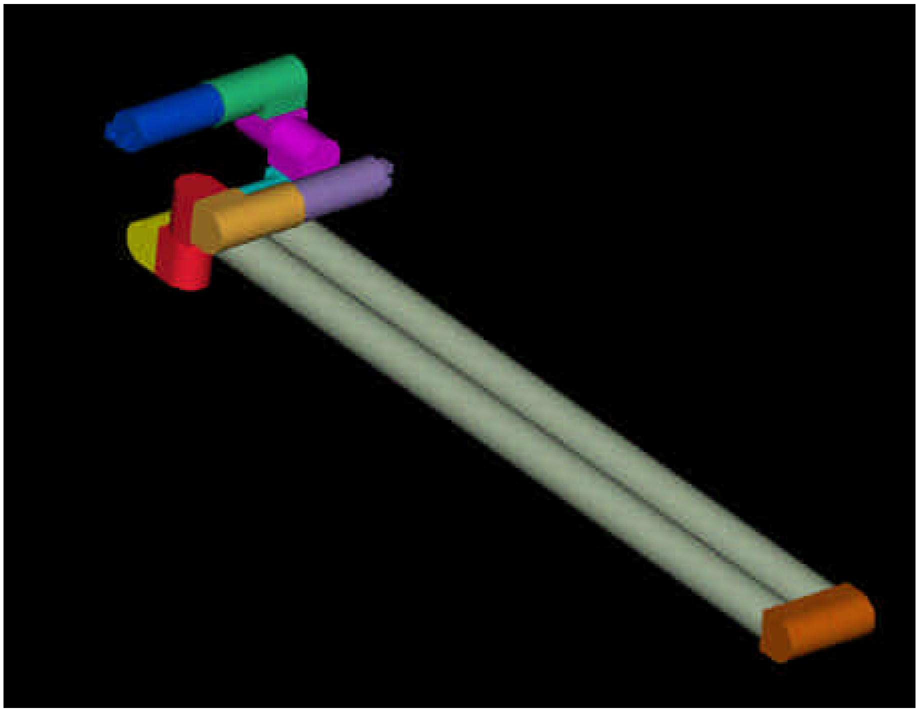

Figure 5-5 Robot 3D Model (stowed)

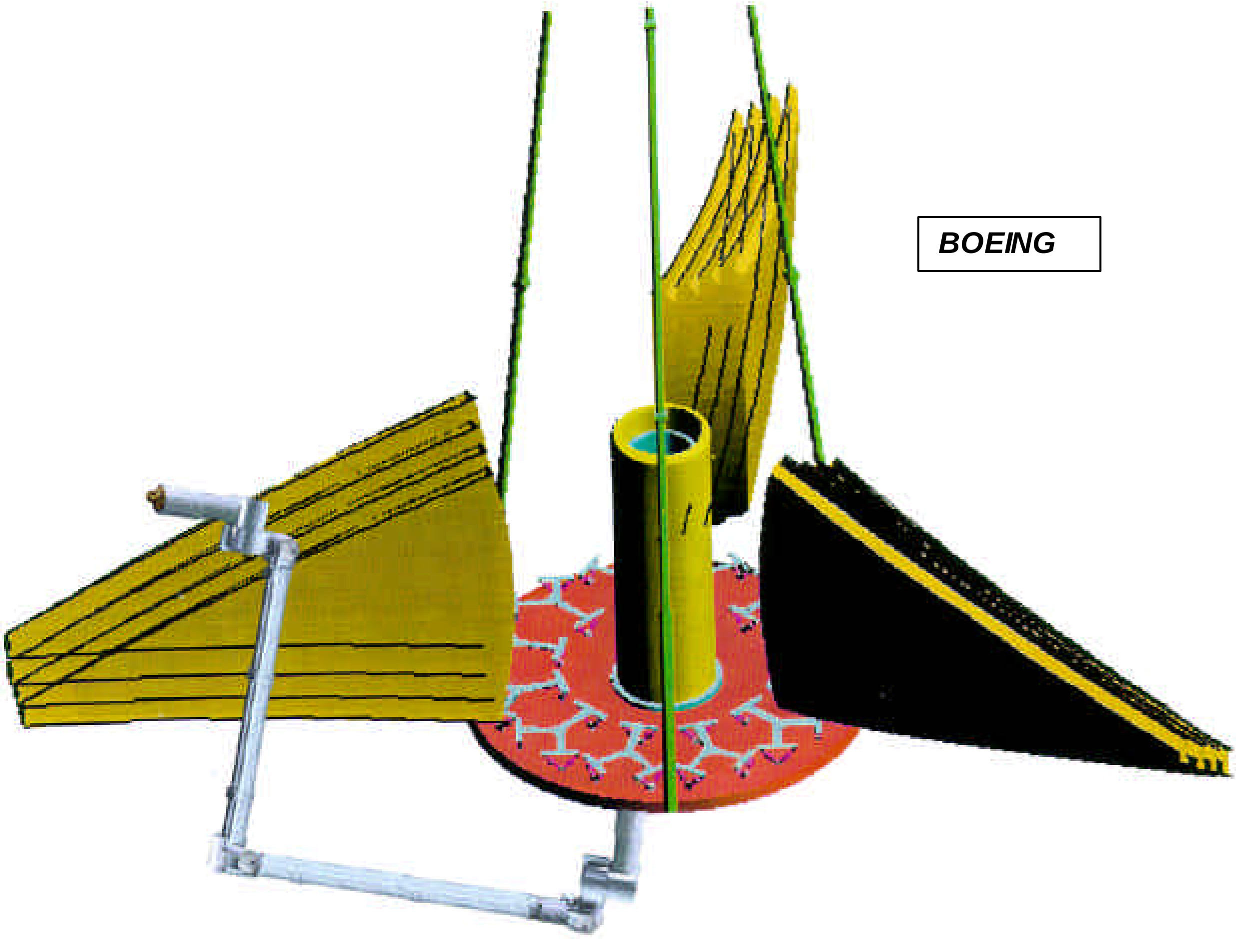

Figure 5-6 NGST Robot Performing Telescope Assembly

5.3.2 Footholds, Handholds & Bolt Interfaces

The robot will need three types of interface to perform the assembly: footholds; handholds; attachment bolts. The envelopes for these are illustrated from Figure 5-7 to Figure 5-9.

Footholds are the largest, and provide a solid base for robot relocation (walking). They must be capable of taking the high loads at the robot base while it is handling a payload, and provide all the power and data connections the robot requires. It comprises a grapple fixture at the center of a base structure, with an electrical connection whereby power and data is transferred between the robot and the spacecraft. It will have a visual target aligned with the end effector cameras, to assist the robot positioning during grapple operations. It may also include some form of physical mating e.g. V-guides, keyways or latches, to achieve a rigid, zero backlash interface, and to support the loads generated during robot operations.

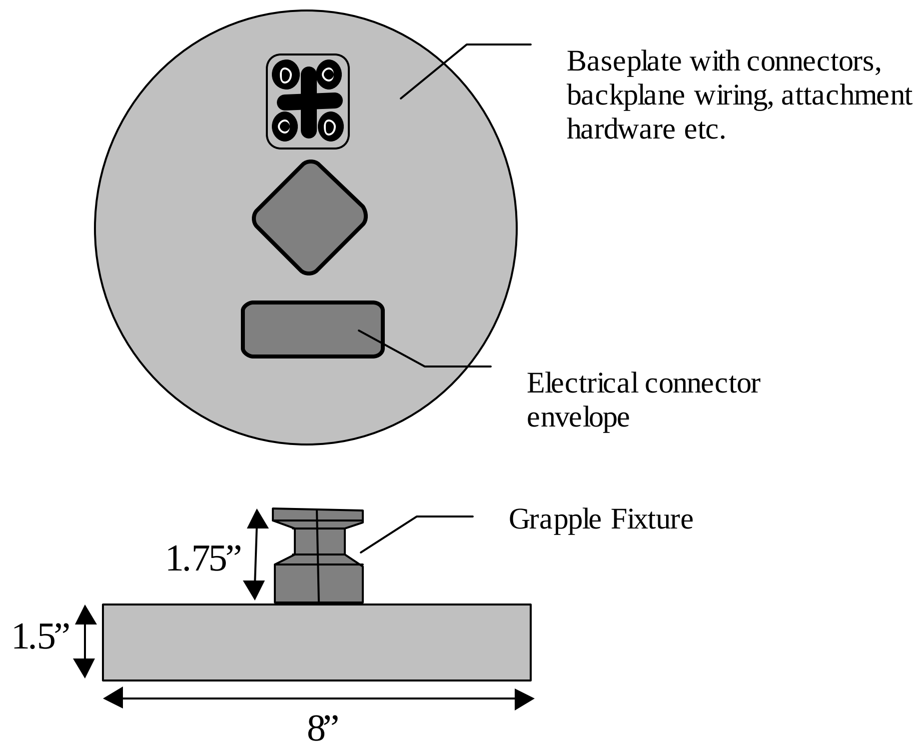

Figure 5-7 Foothold Envelope

A handhold is of similar design, but may be lighter weight as it is subjected to lower loads at the payload/robot interface. It will have a grapple fixture at its center, but may or may not require a power and data connection. It will have a visual target identical to that of the foothold. It may have a means to physically mate the end effector and payload, but if so, to save mass, it could be smaller than that of the foothold because of the smaller loads.

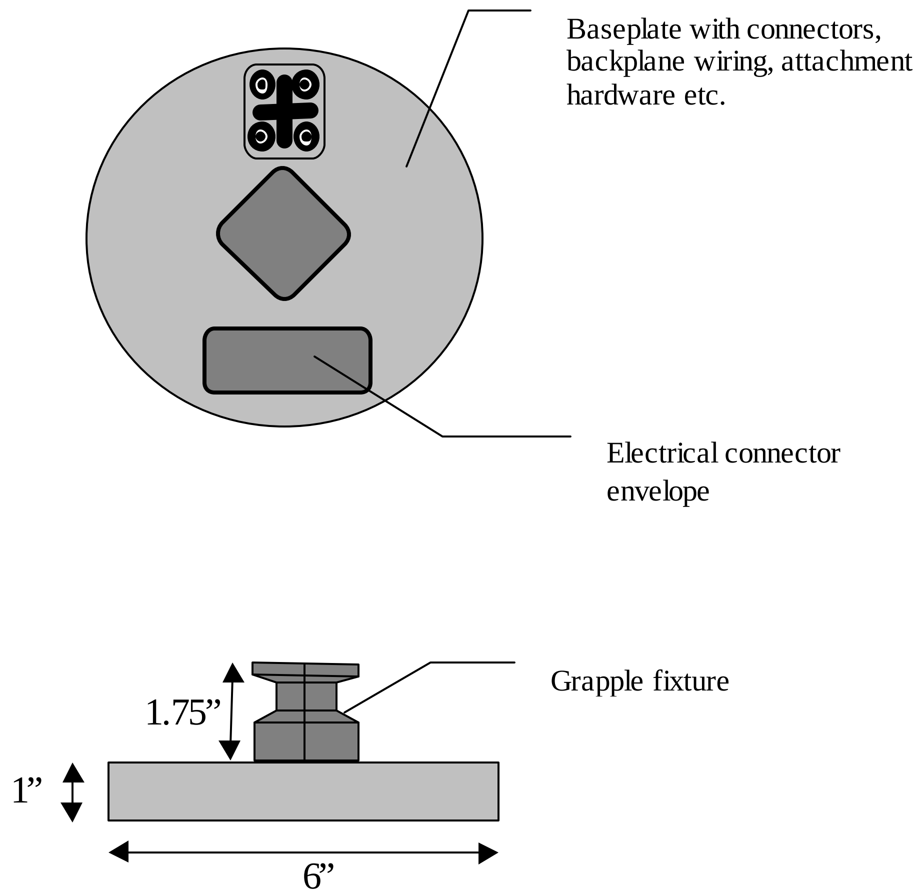

Figure 5-8 Handhold Envelope

The attachment bolt interface permits the robot to undo a bolt or latch. It differs in function from the handhold in that the payload is never transported by this interface and therefore is subject to minimal loads from robot grappling and bolt tightening/loosening. Bolts are tightened or loosened in situ. Removal of a final attachment and picking up the payload will be done using a handhold. The bolt interface will utilize the same grapple fixture and target as the footholds and handholds, to locate the end effector and react the nut driver torques. It has no electrical connection.

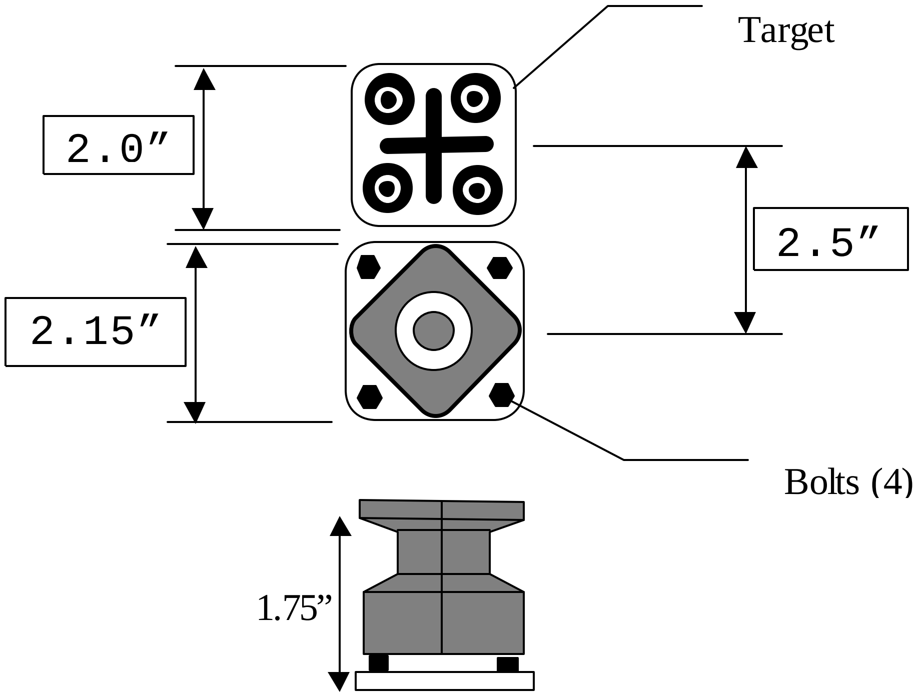

Figure 5-9 Bolt Interface

A conical stay-out zone is recommended above each micro fixture to ensure the robot has sufficient access to grapple. This suggested zone starts at an 8” (20 cm) circle at the plane of the base of the micro fixture, and extends conically at an angle of 30 degrees to the vertical, for 2 meters above that plane. This is illustrated in Figure 5-10.

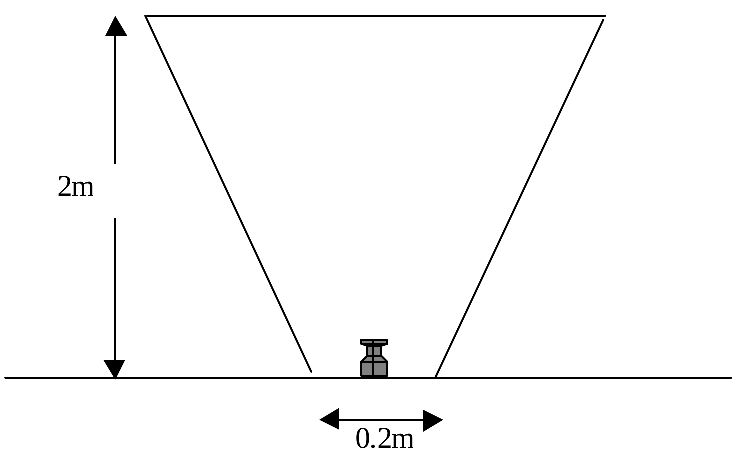

Figure 5-10 Suggested Grapple Fixture Stay-Out Zone

6 PERFORMANCE ANALYSIS

Performance estimates for the NGST robotic system are somewhat premature, since the telescope design concept for robotic assembly is still in development. An attempt has been made to estimate some of the performance parameters based on Spar's robotic experience and the requirements for the robotic system, as they are currently understood. The values quoted are preliminary estimates only. Assumptions and conditions that affect these estimates are defined wherever possible.

6.1 Reliability and Failure Tolerance

The robotic system has been analyzed from both reliability and failure tolerance perspectives. Failure tolerance addresses it from the viewpoint of the effect of component failures on safety. It is directed primarily towards the electrical and electronic elements of the system. Reliability considers the overall probability that the system will be able to complete the mission. Both "one walking robot" and "two walking robots" solutions have been considered. A two-robot system will incur mass and cost penalties but offers greater reliability and failure tolerance.

6.1.1 Failure Tolerance

6.1.1.1 Two-robot System

From a failure tolerance perspective, the 2-robot system has significant advantages. If each robot is 1-fault tolerant, then the overall system is three-fault tolerant, provided the second robot can always remove the first when it fails and complete the mission. In practice, this may not be fully achievable.

The most challenging scenario would be the second (and disabling) failure occurring in the primary robot as it is transporting a component. In the worst case, the back-up robot would experience a single failure prior to reaching the scene. The back-up robot must grapple the component and place it into its destination location, or some temporary restraint where it cannot drift off into space. It could do this with the primary robot still attached. Alternatively, the primary robot may be detached, but only after the back-up robot has grappled the component. The back-up robot must then remove and stow the failed primary robot before completing the mission. The design issues to solve are:

⇒ location of two grapple fixtures on each component

⇒ means to either remotely release failed robot's grasp of component or to limp failed robot so back-up can stow component

⇒ locations to temporarily park a component (wherever the failure may occur)

⇒ locations to stow a failed robot (wherever the failure may occur)

⇒ sufficient extra footholds to permit back-up robot to approach failed primary robot and perform the recovery operations

⇒ sufficient cameras to accomplish this non-nominal operation

As stated, to be a truly 3-fault tolerant system, the back-up robot must be able to recover the failure of the first robot, remove it and complete the mission even when it has suffered a performance-degrading single failure itself. The extent to which the system can be designed to ensure mission success in this event determines the value of having the second robot.

6.1.1.2 One-Robot System

An alternative to the 2-robot system described above is a single robot, perhaps with a higher level of redundancy, e.g. a two-fault tolerant robot. This clearly would not match the 2-robot system in terms of fault tolerance, unless the task of recovering the mission using a back-up robot proved to be untenable.

6.1.1.3 Specification

In the 2-robot system, each robot is essentially 1-fault tolerant. 2-fault tolerance is specified for critical failure modes that could result in the loss of the mission, and where the back-up robot is of no assistance, namely inadvertent release of a payload (or the foothold), and joint runaway. The 2-robot fault tolerance specification is:

- The robot shall be designed such that no single failure will prevent a back up robot from removing it and completing the mission.
- The robot shall provide interfaces for its removal by a back-up robot from an attached payload in the event of a failure.

In the 1-robot system, the robot is essentially 2-fault tolerant. For the critical failures of inadvertent release of a payload (or foothold), and joint runaway, there is little benefit in exceeding the specification for the 2-robot system. The 1-robot fault tolerance specification is:

- No two failures shall prevent the robot from completing its mission
- No two failures of the robot system shall result in damage to the spacecraft (critical hazard).
- No two simultaneous failures shall result in the uncommanded release of an attached payload.
- No two simultaneous failures shall result in uncommanded joint motion.

6.1.2 Fault Tree Analysis

At this stage, when the design is still young and few details have been defined, it is difficult to perform a bottom-up failure modes and effects analysis (FMEA). It is however possible, and very useful, to perform a fault tree analysis. Generation of the operations sequences (defined in Section 4) enables a top-down look at what could go wrong during the telescope assembly mission. The results are presented in Table 6-1 below.

The criticality levels indicated are based on the following scale:

Criticality 1 - Any event that potentially could cause loss of the entire mission

Criticality 2 - Any event that potentially could cause some loss of mission function or degraded mission performance

Criticality 3 - Any event that potentially could cause degradation of the robotic system and or delays in the spacecraft assembly operation

Criticality 4 - Any event that causes none of the above

Fault	**Criticality**	**Possible Causes**	**Reasons**	**Mitigation**
Robot fails to respond to initialization command	3	Spacecraft communications failure		
		Robot communications failure	Failed connection / component	Backup communications channel
Robot launch restraints fail to release	3	Command not received by actuator	Failed connection / component Software error	Redundant circuit Design & test for reliability
		Restraint actuator fails to release	Actuator failure Physical damage to restraint system Thermal stresses in restraint system	Redundant actuators Design for launch loads Thermal control heaters
Robot fails to complete a step-over relocation	3	Failure in foothold electrical system	Failed connector / wiring	Design & test for reliability
		EE not positioned correctly for grapple	Camera failed Lights failed Target damaged / obscured Robot position control failed	Backup camera Backup lights Robust design Redundant electronics, circuitry

			Robot joint failed	Ops possible with 1 joint failed
		EE failed to grapple	Gripper motor failed Gripper jammed Foothold damaged	Redundant windings, electronics Jaw profile, mechanisms designed & tested for reliability Ops possible with 1 failed foothold
		EE failed to engage umbilical	Umbilical drive failed Robot connector damaged Foothold connector damaged	Redundant windings, electronics Shielded, mate attempted only when properly aligned Recessed for protection
		Robot electronics failed to switch successfully	Robot control electronics failed Control software error	Redundant electronics Design & test for reliability
		Command not received	Failed connection / component Software error	Redundant circuit Design & test for reliability
Robot fails to pick up component	3	EE not positioned correctly for grapple	Camera failed Lights failed Target damaged / obscured Robot position control failed Robot joint failed	Backup camera Backup lights Robust design Redundant electronics, circuitry Ops possible with 1 joint failed
		EE failed to grapple	Gripper motor failed Gripper jammed	Redundant windings, electronics Jaw profile, mechanisms designed & tested for reliability

			Component damaged	Robust design, backup grapple point.
		EE failed to undo attachment bolt	Nut runner drive failed Nut runner jammed / misaligned Nut runner generates insufficient torque Component damaged Component attachment bolt seized	Backup drive Design & test for reliability Choose adequate design margins Robust design Design & test for reliability
Robot fails to place component	3	Component not positioned correctly	Camera failed Lights failed Target damaged / obscured Robot position control failed Robot joint failed	Backup camera Backup lights Robust design Redundant electronics, circuitry Ops possible with 1 joint failed
		Component insertion fails	Component damaged Attachment on structure damaged Robot generates insufficient insertion force	Robust design Robust design Choose adequate design margin
		Component tightening fails	Nut runner / tool drive failed Nut runner / tool jammed / misaligned Nut runner / tool generates insufficient torque	Backup drive Design & test for reliability Choose adequate design margins

			Attachment bolt damaged	Robust design
Robot fails to stop on command or at end of autosequence	1,2	Stop command not received	Robot communications failure	Backup communications channel
		Stop command not generated	Computer failure Autosequence malfunction	Redundant hardware Software testing & verification
		Power to motor not shut off	Electronics failure	Redundancy, testing
Component collides with structure	1,2	Robot fails to stop	(See failure above)	(See failure above)
		Excessive error in robot positioning	Joint encoder failure Loss of robot structural integrity Motion command incorrect Error checking failed to stop robot	Redundant components Robust design Autosequence verification Software testing & verification
		Component incorrectly grappled	Jaws failed to seat correctly	Fail-safe design
		Component damaged (geometry has changed)	Prior collision Load limits exceeded	Visual inspection using worksite cameras

Robot inadvertently releases component	1	End effector release command sent in error	Command signal error	Error checking & signal coding
		End effector jaw drive motor activated without release command	Circuit fault	Electronics design & test
		Component not correctly grappled in the first place	Jaws jammed	Jaw, grapple fixture design, grapple sensor
		Failure of end effector mechanical component	Design / manufacturing defect Load limits exceeded	Design checking, part inspection Selection of appropriate operational constraints

Table 6-1 Fault Tree Analysis

6.1.3 Reliability Analysis

The reliability of the robotic assembly operations is perhaps the most important design requirement. As mentioned, an assembly reliability of 0.99 and a target of 0.999 have been used for this study. Mission reliability is dependent on the operations to be performed. As with the failure analysis, the design is too immature to perform a bottom-up reliability analysis, so a top-down approximation for system reliability has been done. Since the system concept is based broadly on the SSRMS and SPDM heritage, system reliability numbers are derived from this work. The results of the analysis, and assumptions made, are presented following.

Based on the operations sequences defined in this report, and typical task durations based on Spar' s experience, the total assembly time has been estimated at 100 hours. A breakdown is shown in Table 6-2. This assembly time is used in the reliability calculations.

Operation	**Duration**	**Quantity (per mission)**	**Total Time (hours)**
Robot Step-Overs	50 minutes	12	10
Component Transfer	1 hour 30 minutes	30	45
Bolt or Latch Tighten/Release	30 minutes	40	20
Overhead Operations / Waiting	----	----	25
TOTAL MISSION:			**100**

Table 6-2 Telescope Assembly Mission Duration

For the 2-robot system, non-operational reliability of the back-up robot (i.e. chance of failure while it is in stand-by mode) is included. For the 1-robot system, the robot is assumed to be 2-fault tolerant. This will not result in great gains in reliability, however, since the driver for reliability are the elements that cannot readily be made redundant (joints, gearboxes, bearings etc.) The numbers presented include reliability of the entire robot system, plus the grapple fixtures, and the video system. The telescope, the communications system, and the operator are considered external to the robot, and have not been included in the calculations. The reliability of the robotic systems over the course of the assembly missions is roughly estimated, based on this preliminary analysis to be:

0.998 for the 2-robot system

0.955 for the 1-robot system

These numbers will have to be re-evaluated when the robotic requirements and robot design are better defined.

The assumptions are:

⇒ Mission duration of 100 hours

⇒ Back-up robot in a 2- robot system can always remove the first (no impact on mission time considered)

⇒ Non-operating failure of back-up robot included

⇒ No allowance for non-operating failures prior to start of assembly operations (may be important if assembly takes place long after launch)

⇒ Calculations include grapple fixture reliability, and video system reliability

⇒ Failure rate of launch restraints or enclosures not included

⇒ Failure rate of attachment mechanisms not included

⇒ Failure rate of telescope hardware not included

⇒ Failure rate of communications system not included

⇒ Operator errors not considered

6.2 Mass Calculations

The mass estimates are based on SPDM experience, with the assumption that improvements in technology will be realized prior to construction of an NGST robot, resulting in mass reductions of approximately 30% from existing technology.

Mass of a 2-robot system = 275 kg. (600 lb.)

Mass of a 1-robot system = 165 kg. (360 lb.)

The assumptions for these calculations are:

- Includes all robot hardware including cameras and launch restraints
- Does not include:
  - Footholds and associated wiring harness on the telescope[2] (foothold mass assumed to be 1kg., harness at 1.0 kg/m)
  - Handholds and associated wiring harness on the telescope[2] (handhold mass assumed to be 0.5kg., harness if required at 0.5 kg/m)
  - Grapple fixtures, bolts, latches etc. on the telescope[2]
  - Communications system
  - Power supply system
  - Temporary storage locations for components, failed robot

[2] Quantities of footholds, handholds, harness, grapple fixtures, bolts and latches etc. associated with the robotic assembly to be determined by Boeing in the development of the telescope design

6.3 Forces & Torques

The goal of the design of assembly mechanisms and operations is to minimize forces and torques. In that way, the size of the robot can be minimized.

Boeing has proposed the use of an attachment system called the ZipNut™ that is the ISS baseline for some EVA and EVR activities, and was employed on the Hubble Space Telescope. It requires approximately 5N force to insert a screw into the ZipNut™. Typical ORU bolt removal torque is 30 Nm.

On this basis, preliminary values are suggested of 10N force and 5Nm moment to be applied by the robot in free motion, and 50Nm of torque capability from the end effector nut-driver.

6.4 Accuracy

Accuracy requirements for the NGST robot grappling are based on Spar micro fixture data. The permitted misalignments are up to a maximum of:

+/- 10 degrees

+/- 0.4 inches

Similar accuracy levels can be assumed for positioning of components prior to their insertion into a restraint or latch. The restrain/latch design will align the component to achieve the desired accuracy for the finished assembly.

6.5 Power Needs

Some very preliminary numbers, based on MSS experience are given below. Note that these are top-down estimates, and as such do not reflect specific design characteristics of the NGST robot. Actual operational requirements, joint design choices, and many other factors will affect these values. Preliminary power estimates (including thermal requirements) per robot are:

500 W peak operating

300 W average operating

150 W keep-alive

6.6 Data Needs

These numbers are ballpark estimates since the robot design is not well defined. They are based on typical values that might be expected. The bandwidths can be split into telemetry and video. Video data is transmitted from space to ground only, and for data in this direction (downlink), it is the driver.

Telemetry uplink ~ 5 kbps

Telemetry downlink ~ 50 kbps

Video downlink ~ 12 Mbps (assumes three full frame video channels @ 256-bit color, 200:1 MPEG compression)

Telemetry uplink bandwidth is low because local autonomous control is assumed, and commands will be simple and not time critical. Reductions can be made in the video bandwidth by considering transmission of still images at a lower frequency. This option depends on the control architecture design.

6.7 Thermal Control

The robot will require heaters during storage, until it is activated for assembly operations. This requirement can be minimized by the use of an enclosure. The back-up robot will require keep-alive power while it is in stand-by mode, and the primary robot may require a small amount of heating during assembly operations, particularly if this is performed in the shade. Heaters will be controlled automatically by thermostat. The electrical power must be provided by the spacecraft through the robot's foothold attachment.

6.8 Ground Station and Robot Control

A practical approach to ground control of the assembly operations is the use of up-linked autosequences and local autonomous control. The operator uploads a pre-planned set of operations which have been determined (through simulation) to be safe for the MSS to perform. He can choose the scope and complexity of these activities. It is much safer and more robust than attempting to control the robot via hand-controllers when significant latency is present and there is a risk of communications loss. A heartbeat may or may not be necessary depending on whether loss of communication during execution of an autosequence requires the autosequence to be stopped.

This approach offers many benefits, including the potential to greatly reduce the uplink and downlink bandwidth requirements since the operator does not need full motion video and there is no real time data to be uplinked. Because of the slower rate of operations, downlinked digital data and telemetry can utilize a smaller bandwidth. The greatest benefit, however, is its robustness.

The suggested ground control station configuration for the non-real-time approach is:

- no hand controllers
- frame-based video down-link
- downlink of digital data (joint angles, health data etc.)
- packetized uplink of autosequences
- off-line and real-time simulator
- predictive displays to assist in overcoming latency
- 3D vision display for enhanced operator monitoring

6.9 Cost Analysis

A cost target of US$50M based upon a somewhat arbitrary budget allocation of 10% of the NGST build costs was set for manufacture of an NGST robot. This would include non-recurring design costs, manufacture, assembly and test. Research and development costs, and launch and operation costs, are not included. It is premature to estimate with any degree of confidence the cost of design, development and production of an NGST robot until the design concept is better defined. It is anticipated, however, that a very aggressive approach to the program would be required, utilizing MSS design heritage and/or commercial off-the-shelf components in order to meet this cost target.

7 CONCLUSIONS

This report has presented a preliminary conceptual design for a robot that is compatible with a Boeing-developed concept for a robotically assembled NGST. A 3D model of the robot concept has been created using Pro Engineer design software. This model, delivered with this report, defines the robot geometry, kinematics and joint motion limits. Its purpose is for use in conjunction with compatible Boeing models of the telescope, to develop an animated 3D computer model that illustrates the robotic assembly of the NGST.

Robotic assembly operation sequences were developed as a starting point in the development of the robot system concept. In the absence of well-defined requirements, and with ongoing progress on the telescope design by Boeing, some of this data may have been superceded. The mass, cost, and performance data provided in this report for the NGST robot are regarded as preliminary estimates only. Estimates include mass, size, positioning accuracy, forces and torques, power needs, and the evaluation of launch configurations. These can be updated, and the confidence level improved, as the telescope design concept and assembly operations evolve.

The proposed concept for the NGST robotic system is based on a walking robot. The walking function provides the maneuverability and versatility necessary for the assembly operations, especially for access to the secondary mirror. The foothold infrastructure on the spacecraft is the primary overhead for walking robots. This comprises sufficient footholds to perform the assembly with back-ups, and the connecting electrical harness. Top level designs for footholds, handholds and bolt interfaces have been provided to Boeing in support of their telescope design activities. The only other viable solution is a transported robot that needs some means of being moved to the various assembly locations. This mechanism, be it a crane, telescoping post or whatever, is likely to add more mass than the foothold infrastructure for a walking robot.

Reliability is an important driver for a robotically assembled NGST. For this reason, both a 1-robot and a 2-robot system were considered in terms of fault tolerance and reliability. If each robot is truly 1-fault tolerant, then the system becomes 3-fault tolerant. Assuming that the back-up robot can complete the mission when the primary robot fails, then the addition of the second robot has been estimated to improve system reliability from about 0.955 to about 0.998. In principle, a two-robot system offers better fault tolerance and reliability. In practice, this may not be fully realized, since there may be some instances where the primary robot has failed due to two faults, and the back-up robot (perhaps degraded by one failure itself) cannot complete the mission. The degree to which the backup robot can or cannot overcome a failure to the primary robot determines the benefit of opting for a two-robot system. This topic warrants further investigation when the telescope design and assembly operations are more clearly defined.

Since the NGST robot (unlike the MSS or SSRMS) will be on an unmanned craft, remote operation will be necessary. Ground teleoperation will be an important element of the robotic system. The presence of signal latency of several seconds (even if construction is performed in a low earth orbit), possible bandwidth limitations, and risk of signal interruptions, all impact the performance of the assembly operations by a ground-based operator. This subject has only been touched on here, but it must be an integral part of the telescope assembly and robot system design.

In order to minimize development costs, the proposed robot conceptual design relies heavily on utilization of MSS heritage. In a very general sense, the NGST robot needs the reach and symmetry of the SSRMS and the dexterity of the SPDM. Exactly how and how well this can be accomplished must be determined through reach and operations analyses. It may be useful to view the NGST robot concept as a single SPDM arm, scaled down in terms of joint and boom diameters, but with longer booms, and with a small end effector at each end.

Finally, although a cost target for the build of an NGST robot system was established, the requirements and design are considered too immature at this stage to offer even a rough order of magnitude cost estimate.

It is recommended that future activities focus first on developing requirements for the robot system based on the telescope design baseline. With a more complete and well-defined set of requirements, the robot design concept can be revisited. The goal is to ensure it is optimized, develop it in greater depth, and produce performance and cost estimates with a high degree of confidence.

REFERENCES

The following documents were used as a reference:

1. Presentation entitled "10 Meter NGST Robotic Assembly Study" by Ronald Muller, Boeing Engineering Services Division, February 17, 1998. Presented at the NGST Quarterly Review Meeting.
2. "Next Generation Space Telescope. Visiting a Time When Galaxies Were Young". Edited by H. S. Stockman. The Association of Universities for Research in Astronomy. NP-1997(05)-016-GSFC/STScl M-9701. June 1997.